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ABSTRACT

This report presents research undertaken as a Vacation Student project, December 2001 to February 2002 which examined an account of human inductive reasoning termed Mental Models theory. The theory predicts that problems for decision-makers arising from basic cognitive processes may have been instrumental in some catastrophic decisions in industry and war fighting. In particular, construction of the mental models used when making critical decisions is vulnerable to both problem complexity and a systematic 'falsity' bias. These vulnerabilities occur because of the limited capacity of human working memory that restricts both the type and the number of component models. An experiment was conducted to test central predictions of the theory.

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Mental Models Theory and Military Decision-making: A Pilot Experimental Model

Executive Summary

This paper examines a recent theory on human inductive reasoning termed Mental Model theory. The theory predicts problems for decision-makers arising from basic cognitive processes. For example, theorists argue that subtle cognitive processes described by mental models may have been instrumental in some catastrophic decisions in industry (eg. Chernobyl nuclear reactor meltdown) and the military (eg. USS Vincennes incident). In particular, construction of the mental models used when making critical decisions is vulnerable to both problem complexity and logically conflicting (false) information. These vulnerabilities occur because of the limited capacity of human working memory. The capacity limitation restricts both the type of information that is represented in mental models and the number of component models. This project aimed to further investigate Mental Model theory for the benefit of future experimental studies in applied Military settings and the design of decision support tools.

An experiment was conducted to test the central predictions of the theory. Twelve subjects (six military, six non-military) were presented with a set of sixteen problems designed to manipulate complexity, the problem domain and the requirement for false information. Comparisons were also made between the performance of the military and non-military groups.

A comparison of the number of problems answered correctly found that the vulnerability to premise falsity extended to the military domain for both military and non-military subjects. Problem complexity, however, was found to have little impact on the number of correct responses. It was also found that subjects responded more quickly when their logic required false premises and more slowly when the question addressed was complex.

Authors

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1. Introduction

1.1 Mental Models and Decision-making

The manner in which humans 'decide' has received a good deal of attention in recent years. In the military domain, the consequences of incorrect decisions can be catastrophic. A dominant applied theory to emerge has been Naturalistic Decision-Making based on Klein's Recognition Primed Decision-making (RPD) model. Rather than being based on formal logic, decision-making is thought to depend on the representation of a situation in mental models and cognitive schemata (Lipshitz & Ben Shaul, 1997). The importance of mental models in decision-making is made evident by a model constructed by Lipshitz and Ben Shaul (1997), shown in Figure 1, that describes the role of schemata and mental models in Klein's RPD model. In the model, schemata drive the situation information that is available to the decision-maker. Schemata, such as experience with the domain, mediate the information search, helping the decision-maker identify the meaningful parts of the information. With the availability of schemata the decision-maker is partially equipped with the ability to check the accuracy of the representation. The information gathered from the situation is then transformed into a mental model that is used to make the decision. Consequently, accurate mental models (i.e. an understanding of 'reality' that accurately reflects 'reality' – or important components of 'reality') are likely to be critical components of successful decision-making.

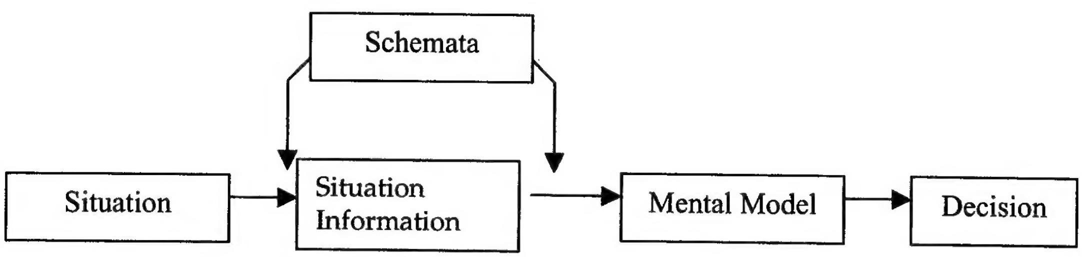

Figure 1. Lipshitz and Ben Shaul's Schemata-driven mental modelling component of Klein's RPD model

Much of the research conducted to date has involved interviews and anecdotal evidence. Given the central place of the concept of 'mental models' in these applied approaches, it is surprising that little empirical research has been conducted in the area.

Recent research lead by Phillip Johnson-Laird has demonstrated that human reasoning ability is determined by the quality and availability of mental models (Johnson-Laird, 1993). According to Johnson-Laird, when evaluating a situation, several models of alternative possibilities are generated based on available information. The mental model or cognitive representation of the situation from which decisions are ultimately made is chosen from this set.

1.2 Mental Model Theory and Human Reasoning

1.2.1 Mental Model Complexity

Central to Mental Model theory is the idea that the limitations of working memory cause many of the problems experienced by human reasoners. Johnson-Laird argues that working memory acts as a cognitive bottleneck restricting human reasoning ability. The limited capacity of working memory has two major effects on the construction of mental models and the ability to draw inferences from these models. First, the greater the number of models that need to be represented explicitly, the harder the inference. Second, conclusions made from premises will be true in only some of the possible scenarios because reasoners typically fail to construct all possible models before deciding on a final conclusion (Johnson-Laird, 1993).

The first of these problems occurs because working memory, since its capacity is finite, does not allow for many models to be represented explicitly (in detail). When the number of models that needs to be represented becomes high (greater than 3) the inference becomes too complex for working memory (Johnson-Laird, 1993). As a result of the limited capacity of working memory, mental models often represent little information explicitly. People typically represent a problem initially with a single explicit model. The models in the initial set represent as much information as possible implicitly (i.e. in semantic terms as in Recognition Priming, see Zambock & Klein, 1999); this information becomes available only when made explicit. In many cases the logically appropriate answer is derived from the initial model set. In these low complexity level inferences the reasoner can easily come to the correct conclusion, while more complex inferences require the implicit information be made explicit (all possibilities realised) and exceed the capabilities of working memory. Thus, the number of explicit models required to support a response mediates the relative difficulty of the conclusion.

In a similar way, Stenning & Yule (1997) have proposed a second constraining affect of working memory that is related to the number of explicit models that a particular problem requires to be thought through. When a particular inference requires a sequence of logic (i.e. a large number of different explicit models) reasoners have typical difficulties in:

a. Forming a sufficiently extensive model set
b. Searching and manipulating the set

Hence, the more explicit models that have to be represented to deal with a situation, the more likely the reasoner will make errors. The complexity and number of explicit models contributes to the level of cognitive demand that confront reasoners such as military decision-makers.

1.2.2 The 'Falsity' Illusion

Recent research by Johnson-Laird in human reasoning has demonstrated that the construction of mental models is also vulnerable to a systematic bias called 'falsity'

(Goldvarg & Johnson-Laird, 2000; Yang & Johnson-Laird, 2000). The falsity illusion occurs because the mental models that reasoners 'build' usually only make explicit what is true while neglecting what is false (Yang & Johnson-Laird, 2000). The reasoner becomes so focused on information that describes what should be in the model that they overlook the information regarded as false that describes what should not be in the model.

In Johnson-Laird's view, reasoners disregard information that might be false (information about things that may not be true) to reduce the complexity of mental effort (to minimise the burden on working memory). Hence, they represent only true assertions in their mental model sets. This kind of logical short-cut can result in what Johnson-Laird called the falsity illusion. It is an error of logic that prevents the reasoner from considering that particular components of a chain of reasoning **may or may not** be true information. As a product of these underlying cognitive processes decisions are sometimes made using inaccurate or incomplete mental models.

So Johnson-Laird's argument is that information on false possibilities **is inherently more complex** than true information and this compounds the effects of complexity upon cognitive effort to the point where an illusory inference can be generated (this is seen, it is proposed, when a decision-makers understanding of 'reality' is very different than 'reality'). The implication of Johnson-Laird's theory is that effective recognition and use of false information requires a great deal more mental effort. In turn reasoners will find a model that 'satisfies' their understanding rather than work through all possible explicit models (based on true or false premises). They do this rather than accurately conclude that a situation is not possible (Goldvarg & Johnson-Laird, 2000). Moreover, only one example of a possibility is needed for the possibility to be true, but all cases need to be ruled out before the possibility can be considered false. The effect of falsity is therefore more significant with multiple model problems (Santamaria, Garcia-Madruga & Carretero, 1996).

Recent research also suggests that reasoners can represent falsity information explicitly in their initial mental models but that it is one of the first pieces of information discarded when an inference becomes difficult. According to the Mental Model theory reasoners try to remember what is false but these 'mental footnotes' are lost when the demands on working memory become too great. Think aloud protocols have demonstrated that reasoners do recognise the importance of false information and make an expressed effort to utilise it but the information is lost as soon as further information is added to the mental model set (Yang & Johnson-Laird, 2000).

1.2.3 Knowledge and Expertise

Reasoners are limited by the extent to which they search for alternative models to validate their existing model. Factors such as general knowledge can lead reasoners to flesh out their mental models more explicitly (Johnson-Laird, 1993). If the initial conclusion is believable, this search for falsifying models is less likely to occur. The believability of a conclusion may stop the search process, causing the reasoner to produce an incorrect

conclusion and inhibiting further information that falsifies this conclusion (Santamaria, Garcia-Madruga & Carretero, 1996). A more extensive search that validates the model by comparing it to alternatives can be elicited by previous experience with the knowledge domain. According to Mental Model theory experience can cause an increase in problem-solving performance by reducing the difficulty of explicit information searches in working memory. Experienced decision-makers familiar with the knowledge domain are less likely to settle for a conclusion that has not been validated by a search for alternatives.

A principal prediction of Mental Model theory is that when equipped with knowledge of the content domain the falsity illusion can be partially overcome (Yang & Johnson-Laird, 2000). Since existing knowledge schemata drives the information search in Lipshitz and Ben Shaul's model, familiarity with the information domain can ensure a more comprehensive representation of the situation. Schemata allows experts in the knowledge domain to produce mental models that although still incomplete are more efficient than those of a novice (Lipshitz & Ben Shaul, 1997). The ability to correctly interpret false information however requires representations of all possibilities and according to Johnson-Laird (1993) knowledge and expertise alone are not enough to overcome the representation problem.

1.3 Mental Model Experimental Research Puzzles

Much of the research by Mental Model theorists investigating logical reasoning has used simple abstract puzzles developed by Johnson-Laird (1993). The format for these puzzles is based on the general format that the reasoner may have available (Brooks, 2000). The puzzles normally contain an assertion that 'Only one of the following statements is true' followed by two premise statements. These puzzles typically contain abstract objects in the premises (marbles, cards) and take the general form:

Only one of the following statements is true:
- **There is A or B or both**
- **There is C and B**

Is C and B possible?

This particular puzzle requires the reasoner to recognise that the possibility of C and B occurring is negated by the concurrent falsity of the first premise. When the first premise is true C and B is not possible because of the falsity of the second premise. Similarly, C and B are not possible when the second premise is true because the falsity of the first premise negates the possibility of a B occurring in the model.

On puzzles such as this that require representation of false premises participants in previous experimental studies have typically answered less than 30% correctly (Goldvarg & Johnson-Laird, 2000; Johnson-Laird, Legerenzi, Girotto & Legerenzi, 2000). The impact of the 'Falsity' illusion is highlighted when compared to a similar puzzle that does not require representation of a false premise. When the question in puzzles of the same

general format as the previous one is 'Is A and B possible?' the number of correct responses is closer to 95%.

1.4 Relevance of Mental Models Theory to the Military

In recent years there has been a very loud call, by Military thinkers, to find means of increasing the speed of Command decision making. This is in order that our own forces might respond faster than an enemy to given situations. The response to this requirement has been dominated by technological improvements to communication and computing equipments. Technological change has not been grounded in a detailed understanding of the decision process. It has been led by improvements in the ability of systems to provide increased quantities of information. To improve the quality of that information and thus the quality of decision-making, it is important to better understand the decision making process.

Mental Models theory is one possible approach to human cognition that may be useful. Indeed, Mental Models Theorists such as Brooks (2000) argue that errors in human reasoning, predicted by their theory, have been instrumental in causing catastrophic decisions made in industry (eg. Chernobyl nuclear reactor meltdown) and Military settings (eg. USS Vincennes shooting down a civilian Iranian airliner during the Gulf war). Applied research in this area aims to minimise these decision-making errors. Ultimately, the research may eventually assist in minimising the vulnerability of decision makers to deception tactics, and ultimately, aid design of tools that can avoid the pitfalls of multiplier effects such as 'falsity' in producing cognitive overload.

1.5 Research Aims and Hypotheses

In light of certain vulnerabilities in logical reasoning made evident by previous research, a working understanding of 'ineffective mental models processing' could be a valuable source of advice for the design of Military command decision-making aids. For example, it is a common belief in the system design world that an interface design should be compatible with an expert operators mental model structure. Several approaches to design emphasise a user-centred engineering approach to design. However, supporting operator's existing mental model processes through system design may result in supporting models that are incomplete or inaccurate if these issues are not clearly defined and addressed. There is currently no testable theory of cognition that can be used to ground the design process. This project aimed to investigate the findings and methods of just a small set of previous research in Mental Models theory. Our aim was to make a first step in framing an empirical research domain that could be applied to the basic human reasoning activities that underpin the Military decision making process.

The present project, then, aimed to investigate empirically a Mental Model theory of human reasoning (Johnson-Laird, 1993). It specifically aimed to investigate the 'falsity' problem predicted by Johnson-Laird's Mental Models theory in regards to Military command decision-making. Based on predictions made from Mental Model theory and

research it was expected that participants in this study would correctly answer more low complexity puzzles than high complexity puzzles, and more true premise puzzles than false premise puzzles. Because of the additional cognitive load it was predicted that participants would take longer to respond to the comparatively harder puzzles.

2. Method

2.1 Participants

The participants in this experiment were 6 Military (4 male and 2 female; Age M = 36, SD = 8.2) and 6 Non Military volunteers (2 male and 4 female; Age M = 21.7, SD = 1) recruited from DSTO-Salisbury.

2.2 Materials

The experiment was conducted using electronic forms created in Microsoft Access (9.0.3821 SR-1). The program presented 16 puzzles to each participant in a random order and recorded the participant's responses and response times for each question. Each of the 16 puzzles used in this experiment with their fully explicit models and correct answers are attached in Appendix 1.

The electronic form contained adapted versions of the experimental puzzles developed by Johnson-Laird (1993). The format of the puzzles was manipulated according to three independent variables: Complexity (high: low), Falsity (true premise: false premise) and Domain (Military: Abstract).

The complexity variable was manipulated by including in half of the puzzles the need to be able to represent a greater number of models simultaneously in order to solve the puzzle. For example the following puzzle only has two different possibilities in the fully explicit model:

Only one of the following statements about the Kamarian Battle group is true:

- **If the component members of the Battle Group include an Aviation Squadron then they will also include Armour**
- **If the component members of the Battle Group include Infantry then they will also include Armour**

  Is it possible for there to be an Aviation Squadron and Armour in the Kamarian Battle Group?

These are the two models that have to be represented to solve the puzzle. The parts of each model that represent false possibilities are in brackets. These possibilities are cancelled out when all contingencies are considered simultaneously:

Model 1.	**(Infantry)**	**Aviation Squadron**	**(Armour)**
Model 2.	**Infantry**	**(Aviation Squadron)**	**(Armour)**

This next example is more complex because four models are needed to make all possibilities fully explicit.

Only one of the following statements about a road convoy is true:

- **There is an Armoured Personnel Carrier in the convoy or there is a Tank in the convoy or both**
- **There is a Mine Clearance Vehicle in the convoy and a Tank in the convoy**

Is it possible for there to be an Armoured Personal Carrier and a Tank in the convoy?

The four models that need to be represented simultaneously to solve the puzzle are:

Model 1.	**APC**	**(MCV)**	**Tank**
Model 2.	**APC**	**MCV**	**(Tank)**
Model 3.	**APC**	**(MCV)**	**(Tank)**
Model 4.	**(APC)**	**(MCV)**	**Tank**

The falsity variable was manipulated by including a statement in half of the puzzles that requires the participants to represent falsity in their mental models when solving the problem, while the other half required representations of true assertions only. To illustrate this, changes to the previous example so that representations of false information are not required to solve the problem are described below.

Only one of the following statements about an impending enemy attack is true:

- **The enemy will approach from Wade valley or Swain valley or both**
- **The enemy will approach from Swain valley and artillery fire will warn of their approach**

1. Representation of falsity required:

   Is it possible for the enemy to come from Swain valley and for artillery fire to warn of their approach?

2. Representation of falsity is not required:

   Is it possible for the enemy to come from both Swain valley and Wade valley?

The first question requires the reasoner to recognise that the possibility of the enemy coming from Swain valley and artillery fire warning of their approach is negated by the concurrent falsity of the first premise. This combination is not possible because the first premise includes an approach from Swain valley and when this premise is false the final model should not include an approach from Swain valley. The correct response is then

'No'. Alternatively, the second question relates to possibilities that occur in the first premise and are not negated by the concurrent falsity of the second. It then follows that the correct answer to the second question is 'Yes'.

Finally, the third variable manipulated was the knowledge domain. The domain variable was manipulated by using the traditional abstract tasks in half of the puzzles and tasks modified to the military knowledge domain for the other half.

An example of one of Johnson Laird's traditional abstract puzzles:

Only one of the following statements about a hand of cards is true:
- **There is a Five in the hand or there is a Four in the hand or both**
- **There is a Three in the hand and a Four in the hand**

Is it possible for there to be a Three and a Four in the hand?

The same puzzle adapted to the Military Knowledge Domain:

Only one of the following statements about an impending enemy attack is true:
- **The enemy will approach from Wade valley or Swain valley or both**
- **The enemy will approach from Swain valley and artillery fire will warn of their approach**

Is it possible for the enemy to come from Swain valley and for artillery fire to warn of their approach?

To control for any response bias each question with a correct 'Yes' response was matched by an equivalent question with a correct 'No' response.

The analysis of data was conducted using SPSS for Windows, Standard version, Release 10.0.7.

2.3 Procedure

The possible impact of complexity and falsity upon human inferential processes was tested using two dependent variables (number of Correct Responses and Time Taken to Respond). Hence, a fully-factorial two way (3x2) repeated measures design was used to test the impact of Complexity (Hi, Lo), Domain (Miltary Non-military), and Falsity (true premise, false premise) upon the number of Johns-Laird type puzzles answered correctly.

In addition, a fully-factorial two way (3x2) repeated measures design was used to test the impact of Complexity (Hi, Lo number of component mental models), Domain (Miltary Non-military context), and Falsity (true premise, false premise as basis for inference) upon the time taken to respond to the Johns-Laird type puzzles. Each participant completed the experiment individually in a quiet room with minimal distractions. The experiment typically took 15-20 minutes for each participant to complete. Presentation of puzzles was fully randomised.

3. Results

3.1 Number of correct responses

Firstly, to compare the performance of our two groups of subjects (Military and non-Military) a one-way analysis of variance was conducted to compare the number of puzzles answered correctly by the two groups. The mean number of questions answered correctly was not statistically different between the Military and Non Military groups ($F(1,10) = 1.91, p = .20$); the means for number correct were 5.67 and 7.50 respectively. Further there was no difference between the two groups in their response to puzzles in the military or non-military context.

Next, a fully factorial two-way (3x2) analysis of variance was conducted to examine the impact of Complexity (Hi, Lo), Domain (Military Non-military), and Falsity (true premise, false premise) upon the number of Johns-Laird type puzzles answered correctly by all subjects.

This analysis yielded a significant main effect only for the independent variable Falsity. Hence, puzzles based on true premises were answered correctly more often than those based on false premises. That effect was significant: at $\alpha = 0.05$, $F(1,3) = 26.651$, $p < 0.0001$. No other main effects reached significance and no significant interaction between the variables of interest was found.

A further test of these subtle effects upon performance on this task involved an assessment of the difference between the mean correct for each type of puzzle against chance (50% correct). A one sample t test comparing mean number correct against the 50%correct criterion revealed that number correct for the False Premise puzzles differed significantly from chance; $t_{11} = -2.996$, $p < 0.05$. Moreover, a one sample t test comparing mean number correct against chance (50%correct) revealed that number correct for the True Premise puzzles yielded no significant difference; $t_{11} = -1.173$, $p > 0.05$.

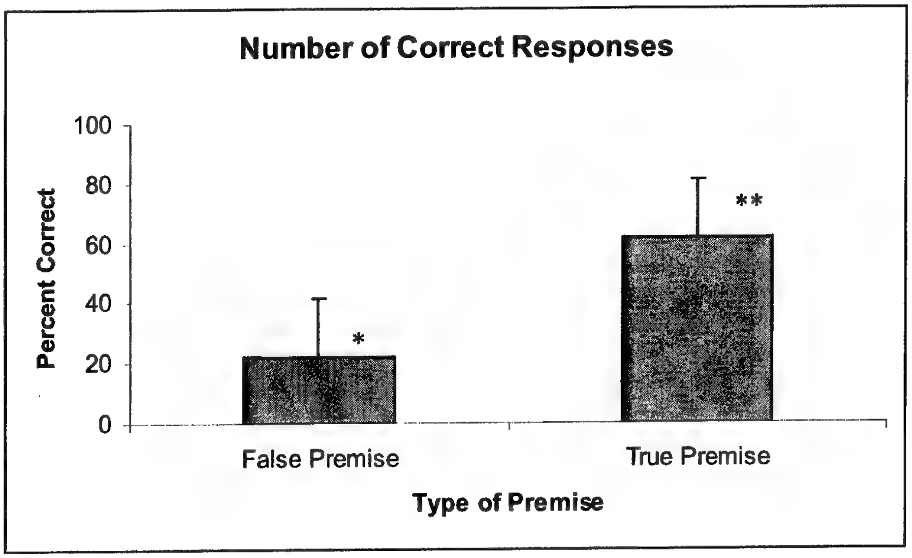

Figure 2, Impact of Premise Type upon Number of Correct responses to Johnson-Laird Puzzles

* *Differed significantly from chance (p<0.05)*
***Did not differ from chance (p>0.05)*

3.2 Time Taken to Respond

To compare the two subject groups used in this study, a one way analysis of variance suggested, as shown in Figure 3, that Military participants answered questions significantly faster than Non Military participants, the mean response times for each group were 34.3 seconds and 54.1 seconds respectively ($F(1,11) = 43.01$, $p < .001$).

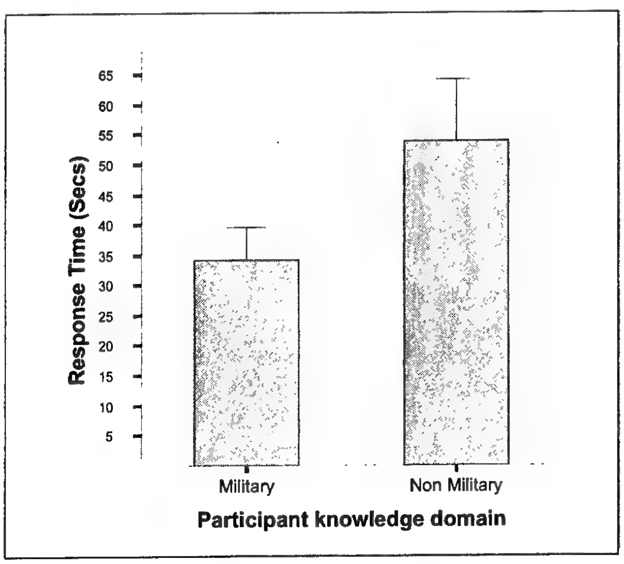

Figure 3. Between groups comparison of mean response times to Johnson-Laird Puzzles

However, Military participants were not any faster than Non Military participants on questions that they answered correctly. Interestingly, it was on the questions that they had answered incorrectly that Military participants spent significantly less time than Non Military participants: $F(1,11) = 7.93, p < .05$). This is shown in Figure 4. The mean response times on questions answered incorrectly by Military and Non Military participants were 29.2 seconds and 52.4 seconds respectively.

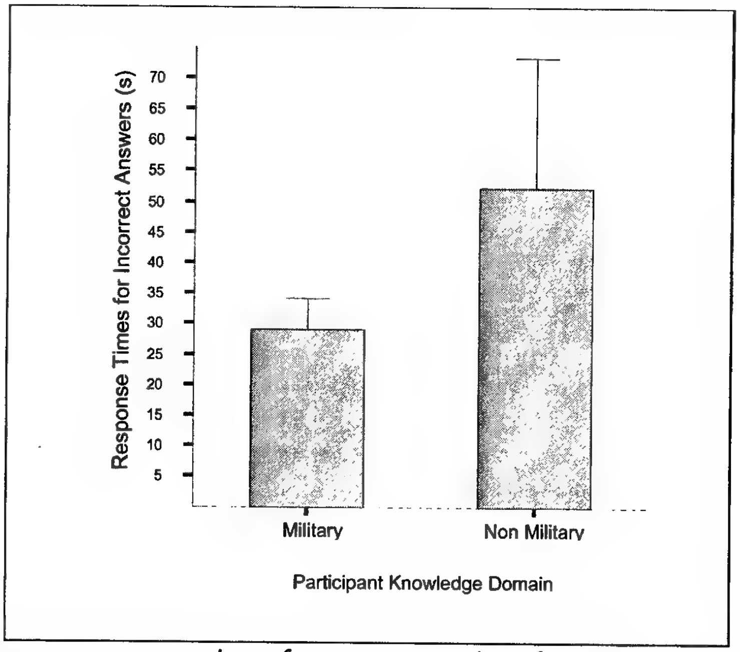

Figure 4. Between groups comparison of mean response times for puzzels answered incorrectly. When answering puzzles incorrectly Military participants answered significantly faster than Non Military participants.

Next, a fully factorial two-way (3x2) analysis of variance was conducted to examine the impact of Complexity (Hi, Lo), Domain (Military Non-military), and Falsity (true premise, false premise) upon the time taken to respond to the Johns-Laird puzzles (correctly or incorrectly).

This analysis found that both Puzzle Complexity and the Type of Premise (Falsity) upon which the Puzzle was founded impacted upon the time taken to respond to the Johnson-Laird puzzles. The effect of Complexity upon Time to Respond was significant : $F(1,11) = 11.86, p < 0.01$. More complex puzzles were associated with a longer response time (as seen in Figure 5).

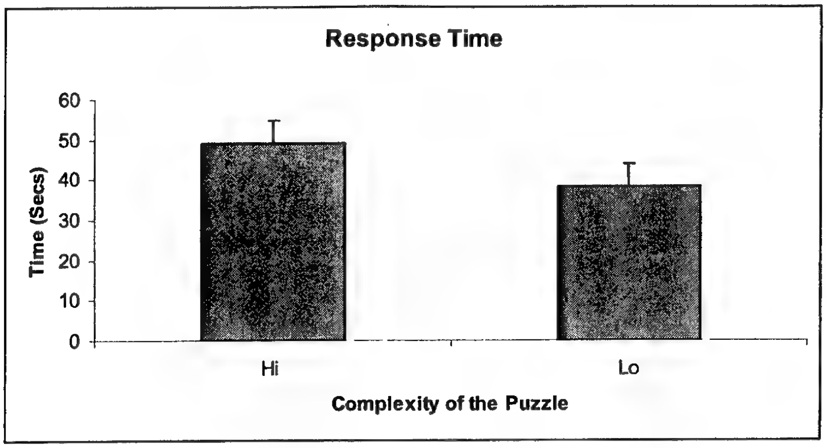

Figure 5, Impact of Puzzle Complexity (number of explicit mental models) upon response time to Johnson-Laird puzzles with standard error bars.

Data analysis also found that puzzle Falsity impacted upon the time taken to respond to the Johnson-Laird puzzles. The effect was significant: $F(1,11) = 8.90$, $p < 0.05$. Perhaps counter-intuitively, puzzles based on False premises were responded to significantly more quickly than puzzles based on true premises (as seen in Figure 6).

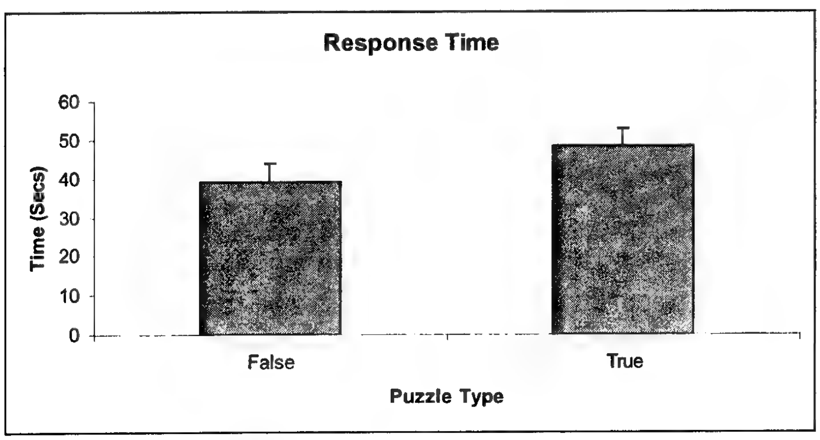

Figure 6. Impact of Puzzle Type (Type of Premise – False / True) upon response time to Johnson-Laird puzzles with standard error bars

4. Discussion

The results of this pilot experimental study supported the hypothesis that a 'Falsity' illusion adversely impacts successful reasoning. It may be, as suggested by Johnson-Laird and his colleagues that additional cognitive capacity is required when premises

underpinning reasoning process are false. This may have led to subjects making error in reasoning, as has been proposed, in a manner sufficient to significantly decrease performance. The hypothesis that puzzles that require a larger number of mental models would decrease performance was also supported. However, the effect was found not in the number of correct responses to Johnson-Laird puzzles but in increased response times of subjects to complex puzzles. Complexity appears to represent a classic cognitive workload effect. This appears not to be the case for the effect of Falsity. Indeed subject responded more quickly to the puzzles framed around false premises. It appears that quite a strong vulnerability toward the issue of falsity exists, at least in the simplistic cognitive tasks that we have employed here.

One of the main aims of this research was to ask the very simple question of whether Johnson-Laird's Mental Model theory of human reasoning and the Falsity illusion might be applicable to the domain of Military command decision-making. In this pilot study only minor amendments to Johnson-Laird's puzzles were implemented to address this question. To make the transition from the previous research, that has examined human reasoning in student populations with abstract tasks toward an applied context will take more extensive analysis. However, our results have uncovered a remarkable possibility that subjects possessing expertise in a particular domain may be more vulnerable to the Falsity Illusion than naïve subjects. This was suggested by the finding that Military experts responded more quickly to puzzles that they answered incorrectly. Military and Non Military participants responded to puzzles framed in both domains with a similar degree of success.

Our findings also suggest that complexity of a problem only slows down the process of cognition, it did not lead to more errors. This is perhaps not surprising in the case of these abstract puzzles. In their criticisms of Mental Model theory, Braine and O'Brien (1998), raise two issues that could explain why the predicted differences in the number of errors between high and low complexity puzzles were not found in this experiment. The first is that the number of models that reasoners can consider before exceeding the limits of working memory has not been adequately determined. The second is that some puzzles labelled by Mental Model theorists as low complexity because of the relatively fewer number of models required for the final model set can actually be harder because in some cases they require additional steps in the reasoning process before coming to a conclusion. Recall that low complexity models in this experiment required 2 models in the final model set and the high complexity required 4. Previous experiments reported by Johnson-Laird (1993) suggest that it is at around 3 models that reasoners experience difficulties with memory load.

The puzzles chosen, requiring 4 models, may not be significantly harder than puzzles requiring 2 models to solve but take significantly longer to resolve. In future investigations of mental model complexity a set of puzzles with a broader range of complexity could be used to determine a 'model threshold' of working memory.

It should be noted that a 'Mental Models' mechanism may not be a sufficient explanation of the manner in which subjects resolve, or seek to resolve, the puzzles presented here. Indeed, several individuals we have shown this paper to have pointed out that they have been able to correctly resolve the puzzles using a formal logic (ie. a sequential reasoning method) approach[1]. Having said that, such an observation does not diminish our initial empirical support for Johnson-Laird's claim that well above 90% of respondents were vulnerable to the predicted error (the Falsity Illusion). Perhaps a disciplined formal logic approach is one way of avoiding errors in inductive reasoning of the kind Johnson-Lard has identified. Moreover, the effect may turn out to be simply a satisficing heuristic. Nevertheless, if the vulnerability to make such error in reasoning were even a common 'tendency', then it deserves attention as an issue for those of us interested in applied cognition.

The results of this experiment support the existence of the 'Falsity' illusion predicted by Mental Model theory and research. In this experiment the effect of the illusion was also demonstrated in Military participants, who assuming experience and knowledge of material in many of the questions (Military domain questions) should, intuitively, have had a distinct advantage over Non Military participants. Instead no difference was found between groups with this small sample size. Overall these results suggest that decision-makers are unable to consider all information in situations that include premises that cannot be confirmed or negated because of difficulties in representing many of the alternative possibilities to the first believable conclusion.

Additional future research is needed to further understand the issues of Mental Model theory and to determine how they should be addressed in the design of decision-making aids. Experimental studies in the future will need larger sample sizes and should explore the context of reasoning on decision-making.

The design of decision-making aids could benefit from determining the number of models that can be represented in working memory and by exploring different methods of facilitating a search for alternative models to help overcome the problems of falsity. An aid that makes the reasoner aware of information or possibilities that are negated or validated by any given conclusion could facilitate a more extensive validating search for example.

In summary, the Mental Models theory suggests that problems in inferential reasoning can arise due to the mechanics of working memory processes. The tendency of working memory to make as much information as possible 'implicit' leaves it vulnerable to conflicting information (information that might be false). Valuable information required for a correct decision can be lost from working memory because of its finite capacity. Design of decision support systems should target problems such as complexity and falsity by easing the load on memory and facilitating the use of fully explicit mental or semantic

[1] Interestingly, both individuals who quickly achieved the correct solution to these problems were trained in formal mathematics.

models. Further research is needed so that these shortcomings in logical human reasoning can be better understood and decision-making ability maximised.

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Appendix A: Experimental Puzzles

Complexity	
High (HFA, HTA, HFM, HTM)	Low (LFA, LTA, LFM, LTM)
Falsity	
True (LTA, HTA, HTM, LTM)	False (HFA, LFA, HFM, LFM)
Domain	
Abstract (LTA, HTA, HFA, LFA)	Military (HFM, LFM, HTM, LTM)

HFA,

Only one of the following statements about a hand of cards is true:

- **There is a Five in the hand or there is a Four in the hand or both**
- **There is a Three in the hand and a Four in the hand**

Is it possible for there to be a Three and a Four in the hand?

Items in brackets cannot be true because the concurrent falsity of the other premise means that it is not possible. These false components are typically not included in mental models.

Four models represent all possibilities:

Model 1.	**5**	**(3)**	**4**
Model 2.	**5**	**3**	**(4)**
Model 3.	**5**	**(3)**	**(4)**
Model 4.	**(5)**	**(3)**	**4**

The correct response is 'No'

Alternative question for equivalent puzzle

Only one of the following statements about the items in a desk drawer is true:

- **There is a Pen in the drawer or there is a Ruler in the drawer or both**
- **There is a Pencil in the drawer and a Ruler in the drawer**

Is it possible for there to be no Pencil in the drawer and no Ruler in the drawer?

Four models represent all possibilities:

Model 1.	**Pen**	**(Pencil)**	**Ruler**
Model 2.	**Pen**	**Pencil**	**(Ruler)**
Model 3.	**Pen**	**(Pencil)**	**(Ruler)**
Model 4.	**(Pen)**	**(Pencil)**	**Ruler**

The correct response is 'Yes'

HTA,

Only one of the following statements about the items on a table is true:
- **There is a bolt on the table or there is a nail on the table or both**
- **There is a pin on the table and a nail on the table**

Is it possible for there to be a bolt and a nail on the table?

Items in brackets cannot be true because the concurrent falsity of the other premise means that it is not possible. These false components are typically not included in mental models.

Four models represent all possibilities:

Model 1.	**B**	**(P)**	**N**
Model 2.	**B**	**P**	**(N)**
Model 3.	**B**	**(P)**	**(N)**
Model 4.	**(B)**	**(P)**	**N**

The correct response is 'Yes'

Alternative question for equivalent puzzle
Only one of the following statements about the coins in a pocket is true:
- **There is a 2 dollar coin in the pocket or there is a 1 dollar coin in the pocket or both**
- **There is a 50 cent coin in the pocket and a 1 dollar coin in the pocket**

Is it impossible for there to be a 2 dollar coin and no 50 cent coin in the pocket?

Four models represent all possibilities:

Model 1.	**2**	**(50)**	**1**
Model 2.	**2**	**50**	**(1)**
Model 3.	**2**	**(50)**	**(1)**
Model 4.	**(2)**	**(50)**	**1**

The correct response is 'No'

HFM,

Only one of the following statements about an impending enemy attack is true:

- **The enemy will approach from Wade valley or Swain valley or both**
- **The enemy will approach from Swain valley and artillery fire will warn of their approach**

Is it possible for the enemy to come from Swain valley and for artillery fire to warn of their approach?

Items in brackets cannot be true because the concurrent falsity of the other premise means that it is not possible. These false components are typically not included in mental models.

Four models represent all possibilities:

Model 1.	**Wade**	**(Artillery)**	**Swain**
Model 2.	**Wade**	**Artillery**	**(Swain)**
Model 3.	**Wade**	**(Artillery)**	**(Swain)**
Model 4.	**(Wade)**	**(Artillery)**	**Swain**

The correct response is 'no'

Alternative question for equivalent problem

Only one of the following statements about the position of a reserve is true:

- **Reserve forces are located in the West or in the North or both**
- **Reserve forces are located in the East and in the North**

Is it possible for there to be reserve forces in the East and none in the North?

Four models represent all possibilities:

Model 1.	**West**	**(East)**	**North**
Model 2.	**West**	**East**	**(North)**
Model 3.	**West**	**(East)**	**(North)**
Model 4.	**(West)**	**(East)**	**North**

The correct response is 'yes'

HTM

Only one of the following statements about a road convoy is true:

- **There is an Armoured Personnel Carrier in the convoy or there is a Tank in the convoy or both**
- **There is a Mine Clearance Vehicle in the convoy and a Tank in the convoy**

Is it possible for there to be an Armoured Personal Carrier and a Tank in the convoy?

Items in brackets cannot be true because the concurrent falsity of the other premise means that it is not possible. These false components are typically not included in mental models.

Four models represent all possibilities:

Model 1.	**APC**	**(MCV)**	**Tank**
Model 2.	**APC**	**MCV**	**(Tank)**
Model 3.	**APC**	**(MCV)**	**(Tank)**
Model 4.	**(APC)**	**(MCV)**	**Tank**

The correct response is 'Yes'

Alternative question for equivalent problem
Only one of the following assumptions in a planned counter-attack is true:

- **The enemy consists of one Battalion or the enemy will have air superiority or both**
- **No other enemy activities elsewhere will affect this plan and the enemy will have air superiority**

Is it impossible for the enemy to consist of one Battalion and for no other enemy activities elsewhere to affect this plan?

Four models represent all possibilities:

Model 1.	**One Battalion**	**(No other En activities)**	**Air Superiority**
Model 2.	**One Battalion**	**No other En activities**	**(Air Superiority)**
Model 3.	**One Battalion**	**(No other En activities)**	**(Air Superiority)**
Model 4.	**(One Battalion)**	**(No other En Activities)**	**Air Superiority**

The correct answer is 'No'

LFA,

Only one of the following statements about a bag of marbles is true:

- **If there are red marbles in the bag then there are green marbles in the bag**
- **If there are blue marbles in the bag then there are green marbles in the bag**

Is it possible for there to be red marbles and green marbles in the bag?

Items in brackets cannot be true because the concurrent falsity of the other premise means that it is not possible. These false components are typically not included in mental models.

Two models represent all possibilities

Model 1.	**(R)**	**B**	**(G)**
Model 2.	**R**	**(B)**	**(G)**

The correct response is 'No'

Alternative question for equivalent problem

Only one of the following statements about the animals on a farm is true:

- **If there are pigs on the farm then there are sheep on the farm**
- **If there are chickens on the farm then there are sheep on the farm**

Is it possible for there to be pigs and no sheep on the farm?

Two models represent all possibilities:

Model 1.	**(pigs)**	**chickens**	**(sheep)**
Model 2.	**pigs**	**(chickens)**	**(sheep)**

The correct response is 'Yes'

LTA,

Only one of the following statements about the books on a shelf is true:

- **If there is an encyclopaedia on the shelf then there is a dictionary on the shelf**
- **If there is a recipe book on the shelf then there is a dictionary on the shelf**

Is it possible for there to be an encyclopaedia and no recipe book on the shelf?

Items in brackets cannot be true because the concurrent falsity of the other premise means that it is not possible. These false components are typically not included in mental models.

Two models represent all possibilities

Model 1.	**(recipe)**	**enc**	**(dict)**
Model 2.	**recipe**	**(enc)**	**(dict)**

The correct response is 'Yes'

Alternative question for equivalent problem

Only one of the following statements about the beads on a necklace is true:

- **If there are wooden beads on the necklace then there are plastic beads on the necklace**
- **If there are metal beads on the necklace then there are plastic beads on the necklace**

Is it possible for there to be no wooden beads and no metal beads on the necklace?

Two models represent all possibilities:

Model 1.	**(metal)**	**wooden**	**(plastic)**
Model 2.	**metal**	**(wooden)**	**(plastic)**

The correct answer is 'No'

LFM,

Only one of the following statements about the Kamarian Battle group is true:

- **If the component members of the Battle Group include an Aviation Squadron then they will also include Armour**
- **If the component members of the Battle Group include Infantry then they will also include Armour**

Is it possible for there to be an Aviation Squadron and Armour in the Kamarian Battle Group?

Items in brackets cannot be true because the concurrent falsity of the other premise means that it is not possible. These false components are typically not included in mental models.

Two models represent all possibilities

Model 1.	**(Infantry)**	**Aviation Squadron**	**(Armour)**
Model 2.	**Infantry**	**(Aviation Squadron)**	**(Armour)**

The correct response is 'No'

Alternative question for equivalent problem

Only one of the following statements about a battle is true:

- **If 1 section is in contact then 3 section is in contact**
- **If 2 section is in contact then 3 section is in contact**

Is it possible for 1 section to be in contact and 3 section not to be in contact?

Two models represent all possibilities:

Model 1.	**(2 section)**	**1 section**	**(3 section)**
Model 2.	**2 section**	**(1 section)**	**(3 section)**

The correct response is 'Yes'

LTM

Only one of the following statements about the position of enemy forces is true:

- **If there are Kamarian forces in Goldvarg valley then there are Kamarian forces in Laird valley**
- **If there are Kamarian forces in Johnson valley then there are Kamarian forces in Laird valley**

Is it possible for there to be Kamarian forces in Goldvarg valley and no Kamarian forces in Johnson valley?

Items in brackets cannot be true because the concurrent falsity of the other premise means that it is not possible. These false components are typically not included in mental models.

Two models represent all possibilities

Model. 1	**(Goldvarg)**	**Johnson**	**(Laird)**
Model. 2	**Goldvarg**	**(Johnson)**	**(Laird)**

The correct response is 'Yes'

Alternative question for equivalent problem

Only one of the following statements about the occupants of a building is true:

- **If there are enemy in the building then there are neutrals in the building**
- **If there are friendly in the building then there are neutrals in the building**

Is it possible for there to be no enemy and no friendly in the building?

Two models represent all possibilities:

Model. 1	**(enemy)**	**friendly**	**(neutrals)**
Model. 2	**enemy**	**(friendly)**	**(neutrals)**

The correct response is 'No'

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Jason Sparkes and Sam Huf

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19. ABSTRACT

This report presents research undertaken as a Vacation Student project, December 2001 to February 2002 which examined an account of human inductive reasoning termed Mental Models theory. The theory predicts that problems for decision-makers arising from basic cognitive processes may have been instrumental in some catastrophic decisions in industry and war fighting. In particular, construction of the mental models used when making critical decisions is vulnerable to both problem complexity and a systematic 'falsity' bias. These vulnerabilities occur because of the limited capacity of human working memory that restricts both the type and the number of component models. An experiment was conducted to test central predictions of the theory.

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